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# Exotic Nuclei and Yukawa's Forces

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**Abstract**

In this plenary talk, we will overview the evolution of the shell structure in stable and exotic nuclei as a new paradigm of nuclear structure physics. This shell evolution is primarily due to the tensor force. The robust mechanism and some examples will be presented. Such examples include the disappearance of existing magic numbers and the appearance of new ones. The nuclear magic numbers have been believed, since Mayer and Jensen, to be constants as 2, 8, 20, 28, 50, ... This turned out to be changed, once we entered the regime of exotic nuclei. This shell evolution develops at many places on the nuclear chart in various forms. For example, superheavy magic numbers may be altered. Thus, we are led to a new paradigm as to how and where the nuclear shell evolves, and what consequences arise. The evolution of the shell affects weak process transitions, and plays a crucial role in deformation. The $\pi$ and $\rho$ mesons generate tensor forces, and are the fundamental elements of such intriguing phenomena. Thus, physics of exotic nuclei arises as a manifestation of Yukawa's forces.

*Key words:* exotic nuclei, shell evolution, tensor force, pion, magic number
*PACS:* 21.30.Fe, 21.60.-n, 21.60.Cs, 21.10.-k

## 1. Introduction

Exotic (or unstable) nuclei have confronted nuclear physics with new phenomena, features and ideas. Although exotic nuclei have been objects of nuclear physics since its very beginning, systematic studies have started only after the discovery of extraordinarily large radius of $^{11}$Li by Tanihata *et al.* in 1985 [1]. This experiment was made possible by the radioactive ion (rare isotope) beam (RI-beam) technology [1], and in fact many


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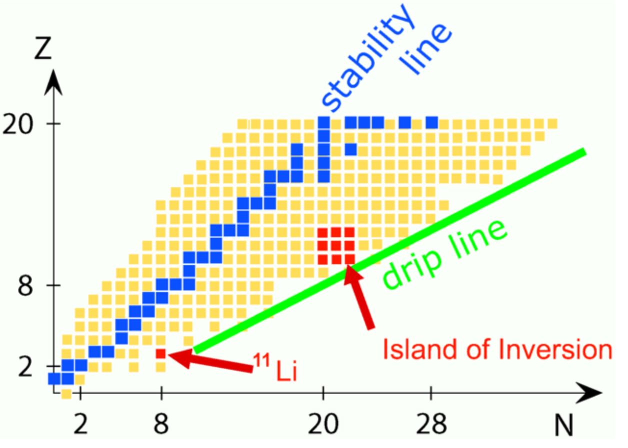


Fig. 1. (color online)Left lower corner of the nuclear chart. Blue squares are stable nuclei, while yellow ones are known unstable nuclei.

experiments have been conducted since then, changing the landscape of nuclear structure physics.

The nucleus $^{11}$Li is known for its the neutron halo, which is a direct consequence of the loose binding of last neutrons. Figure 1 indicates the left-lower corner of the nuclear chart, including $^{11}$Li. One sees that this nucleus can be reached by adding four neutrons to the stable nucleus $^{7}$Li. In fact, in the 90's, light exotic nuclei around $^{11}$Li on the nuclear chart, for which the neutron drip line is not very far, have been studied intensively, and the motion of weakly bound neutrons was the major subject [2].

In the 21st century, besides light ones, heavier exotic nuclei have become objects of systematic extensive studies, partly due to further developments of RI-beam experiments. Figure 1 suggests that the stability line and the drip line drift apart from each other as we move to higher atomic number, $Z$. In fact, contrary to Li isotopes, the neutron number, $N$, increases by more than ten units from the stability line to the neutron drip line for Mg isotopes. One can then raise a question what happens between the stability and drip lines on the nuclear chart. The area between the two lines becomes wider and wider as $Z$ becomes higher, while the nuclei in this area are still well bound except on and very near the drip line.

In this talk, we shall discuss how the structure of many nuclei between the stability and drip lines looks like, what is the underlying mechanism if some changes occur, and what one can expect in exotic nuclei to be explored.

The structure of bound nuclei depends much on their shell structure. Not only single particle properties but also deformation can be strongly influenced by the change of shell structure. The shell structure has been believed to be basically common not only among stable nuclei but also between stable and exotic (unstable) nuclei. The shell structure of stable nuclei has been proposed by Mayer and Jensen in 1949 with magic numbers, 2, 8, 20, 28, 50 ,... [3]. These magic numbers can be conceived from three basic features; (i) short-range attraction of nucleon-nucleon ($NN$) interaction, (ii) density saturation, (iii) spin-orbit splitting. Note that for (i), an isotropic attraction is in mind like the central potential. From (i) and (ii), the Harmonic Oscillator potential can be derived

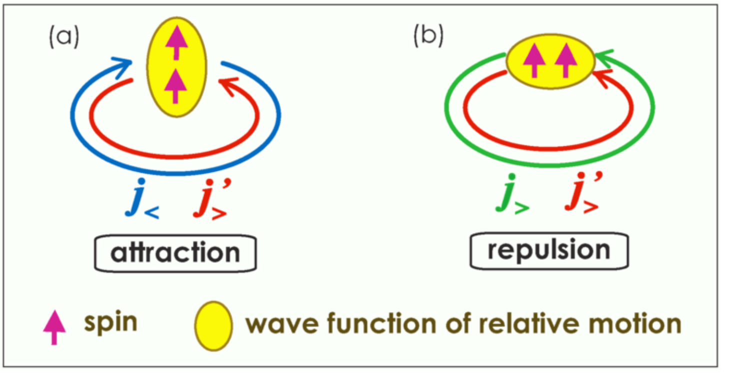


Fig. 2. (color online) Intuitive illustration of the tensor force acting two nucleons on orbits $j$ and $j'$. Taken from Fig. 2 of [6].

[4,5], and the combination with (iii) produces the magic numbers of Mayer and Jensen. Thus, the magic numbers of Mayer and Jensen are quite robust, as they originate in very basic properties. Therefore, as far as the above features (i)-(iii) are considered, the magic numbers cannot be different from Mayer-Jensen's. If different, this is an indication of something additional. In fact, it is a fundamental issue whether or not magic numbers and shell structure remain unchanged in going from stable to exotic nuclei. We shall look for the answer to this question.

The key to this answer has been found recently to be the tensor force [6]. The tensor force is not among the three features mentioned above. While the tensor force itself has been known and studied over half a century, not everything has been clarified. Figure 2 illustrates intuitively how the tensor force works for two interacting nucleons in two orbitals. Here, we use notations

$$j_> = l + 1/2 \quad \text{and} \quad j_< = l - 1/2\,, \tag{1}$$

where $l$ is the orbital angular momentum. Namely, in the former case, the orbital angular momentum and spin are parallel, whereas they are opposite in the latter. The tensor force works only if spins of two nucleons are parallel coupled to the total $S$=1. So spins can be fixed as being "up", but the orbital motion can be in either way (See Fig. 2). If two nucleons are in orbits $j_<$ and $j'_>$, they are moving in opposite directions as in Fig. 2(a). The relative momentum is high at "collision", and the spatial wave function of the relative motion is suppressed along the direction of collision. Thus, the wave function is stretched along the spin $S$, and the tensor force works attractively. If two nucleons are in orbits $j_>$ and $j'_>$, they are moving together as in Fig. 2(b), and the tensor force works repulsively. Thus, the tensor force changes single-particle energy depending on the numbers of nucleons in other orbitals, following the rule proposed in Fig 2 (Fig. 2 of [6]).

Many phenomena in the structure of exotic nuclei have been understood in terms of the tensor force, and the mechanism shown in Fig. 2 always gives us the correct picture immediately. For instance, the magic number changes between $N$=16 and 20 in going from oxygen ($Z$=8) to silicon ($Z$=14) as depicted in Fig. 3(a,b). This change is due to the proton occupancy into the $1d_{5/2}$ orbit and the strong tensor attraction between $1d_{5/2}$ and $1d_{3/2}$ (See Fig. 3(c)). The diagram for this tensor-force is in Fig. 3(d). Figure 3 is a modified version of Fig. 1 of [7]. The abstract of [7] states "The magic numbers in exotic

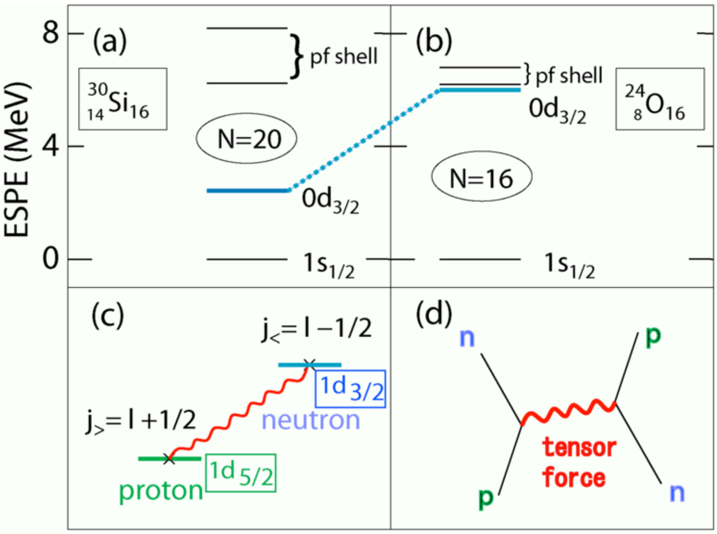


Fig. 3. (color online) Neutron single-particle energies of (a) a stable nucleus $^{30}$Si and (b) an exotic nucleus $^{24}$O relative to $1s_{1/2}$. (c) The major interaction producing the basic change between (a) and (b). (d) The diagram relevant to the interaction in (c). This figure is based on Fig. 1 of [7].

nuclei are discussed, and their novel origin is shown to be the spin-isospin dependent part of the nucleon-nucleon interaction in nuclei". In [7], it was shown that this spin-isospin dependent part produces strong $j_>$-$j_<$ coupling, but the origin of this coupling was not clarified, while the tensor force was mentioned as one of the three lowest order terms in the 1/N$_c$ expansion [8]. More thought was needed for the tensor force, primarily because there was a general belief, at the time of [7], that the tensor force is so complicated and should have nothing to do with single-particle properties.

Many examples of the tensor force effects on the shell evolution have been found since [6]. Figure 4 displays cases to be presented in this talk covering nuclei from *p*-shell to superheavies.

## 2. Shell structure and magic numbers of exotic nuclei

Figure 5 shows the energy splitting between $1h_{11/2}$ and $1g_{7/2}$ orbits of protons in Sb ($Z$=51) isotopes as a function of the neutron number. The splitting is plotted for the variation from the splitting at $N$=64. Schiffer *et al.* reported experimental values [10] as shown in Fig. 5. It was not possible to explain the gradual increase of the splitting within existing mean field models. However, once we calculate this splitting by including the tensor force, the theoretical result showed a remarkable agreement first by a shell-model [6] with the $\pi + \rho$ meson exchange potential [11], and later by a mean-field model [12]. This is the precious case where the tensor force effect has been examined with

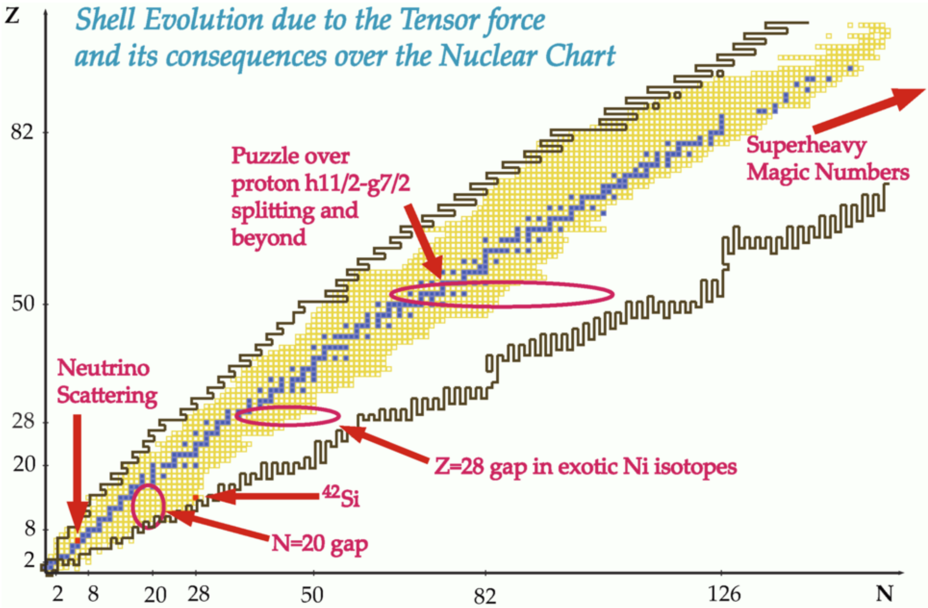


Fig. 4. (color online) Examples of shell evolution due to the tensor. The outer brown lines indicate driplines predicted by Koura et al. [9]. The blue squares are stable nuclei, while yellow boxes are known exotic nuclei.

experimental data over a long chain of isotopes.

In Fig. 5, two mean-field models are used. One is Gogny model [13] with D1S interaction [14]. This model has been very successful, but does not contain the tensor force, similarly to usual calculations by Skyrme model [15,16]. The other model, GT2, has recently been introduced in [12] based on the Gogny model with explicit inclusion of the tensor force, giving rise to a good agreement to experiment as shown in Fig. 5.

Figure 5 contains another important aspect. The theoretical prediction goes up to $N$=104, where the splitting decreases. The D1S result meets the GT2 result at $N$=104, because the tensor force effects are cancelled for the spin saturation. The small increase of the splitting is due to the 2-body spin-orbit force [12]. We emphasize that the effects of the tensor force become evident once the systematic behavior over long isotope chain is obtained.

Figure 6 indicates proton and neutron single-particle energies calculated by two models, D1S and GT2. The proton $1f_{5/2}$ level drops much faster than the others from $N$=40 to 50 in Fig. 6(d). The tensor force attraction is particularly strong between this $1f_{5/2}$ orbit ($j_<$) and the neutron $1g_{9/2}$ orbit ($j'_>$). As more neutrons occupy $1g_{9/2}$, the proton $1f_{5/2}$ orbit is pushed down relative to the other orbits. In contrast, the tensor force works repulsively between $1f_{7/2}$ ($j_>$) and $1g_{9/2}$ orbit ($j'_>$). Figure 6(d) indicates that $1f_{7/2}$ drops more slowly than the others consistently with this rule. The tensor correlation between two neutrons is weaker, but it exists. In fact, the neutron $1f_{5/2}$ level drops in Fig. 6(b) too, as the 2-body spin-orbit force also contributes to this change [12]. Figures 6(a,c) show the results of D1S interaction. Since there is no tensor force, the $Z, N$=28 gaps remain almost unchanged.

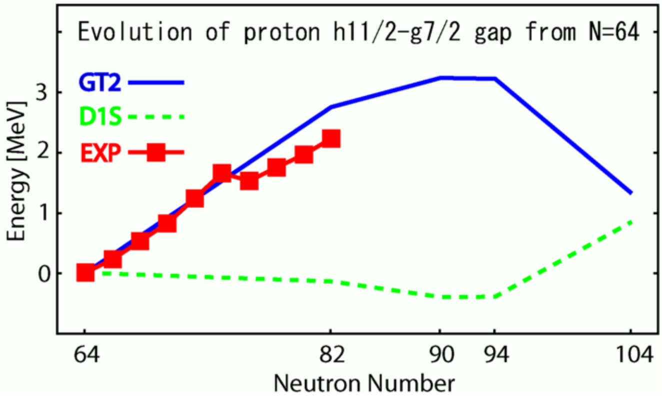


Fig. 5. (color online) Evolution of the proton $1h_{11/2}$-$1g_{7/2}$ splitting measured from the value at $N$=64. Taken from Fig. 4 of [12].

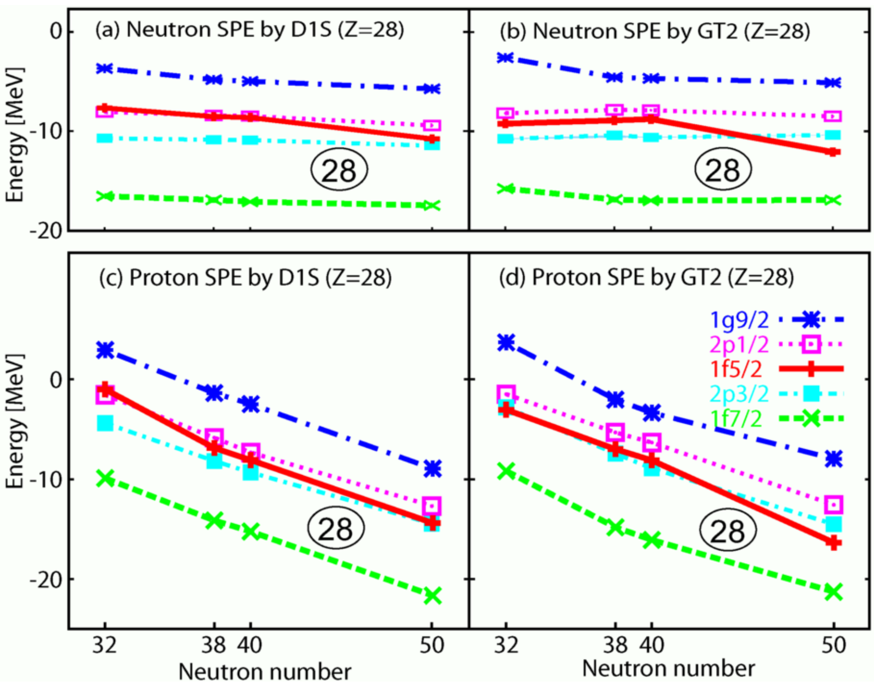


Fig. 6. (color online) Single-particle energies of Ni isotopes calculated by D1S and GT2 interactions. A part of Fig. 1 of [12].

At this point, we mention other theoretical works incorporating the tensor force into mean field calculations. Stancu, Brink and Flocard [17] introduced tensor-like zero-range interaction in 1977. Although this work has been quoted at a modest rate, after the publication of [12] many papers based on this interaction have been written and submitted [18–22]. Relativistic approaches are also being made [23,24]. For the understanding of the shell evolution, it seems that the inclusion of the tensor force in mean field calculations become a standard process due to the impact of [6,12], while the shell evolution has been studied also in the shell model for instance by [25,26].

## 3. Deformation driven by tensor force

From recent analysis of shell-model interaction, the tensor-force component in the shell-model effective interaction is very close to the $\pi + \rho$ meson exchange potential [11]. This seems to be somewhat related to the Chiral Perturbation idea of Weinberg [27]. Along this line, we have obtained a new shell model interaction, and its results are shown in Fig. 7 for exotic Si isotopes in a good agreement with experiments [28–30]. Figure 8 presents the potential energy surface, where the tensor force is switched off in the inter shell channel in one calculation, while in the other the full tensor force is used. The tensor force produces the pronounced oblate minimum, whereas the other calculation gives a spherical minimum. Thus, one sees the crucial role of the tensor force also for the deformation. The nucleus $^{42}$Si has been the object of a debate on its magic nature [30,31]. The present result seem to explain both small cross section and large deformation, but we should wait until the calculation of the cross section. There are many other models and calculations leading to different conclusions [30,31].

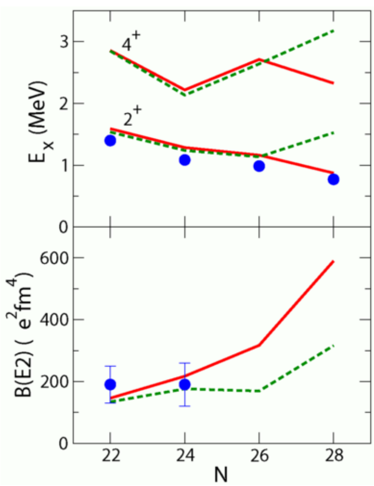


Fig. 7. (color online) $2^+$ and $4^+$ levels (upper panel) and B(E2) values (lower panel) of exotic Si isotopes. Experimental data are from [28–30]. The solid lines indicate full calculations, whereas the dashed lines calculations without the tensor force in the inter shell channel.

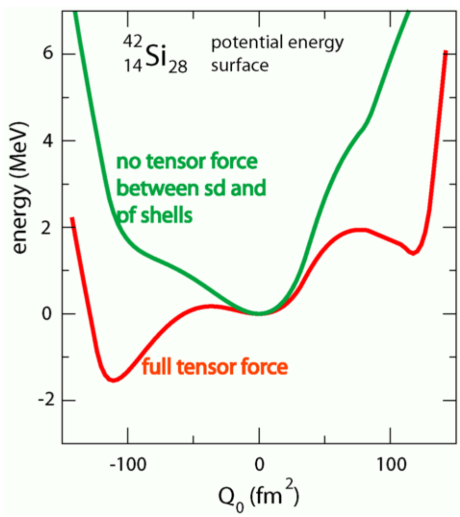


Fig. 8. (color online) Potential energy surface of $^{42}$Si for the present shell model Hamiltonian.

Back to the year 1990, the so-called Island of Inversion was proposed [32] for the nine nuclei shown also in Fig. 1, incorporating earlier studies, *e.g.*, [33,34]. These nine nuclei were predicted to have abnormal ground states with 2p2h excitation from the *sd* shell across the N=20 magic gap. This Island of Inversion is an isolated area in the nuclear chart. However, the constant $N$=20 gap may not correspond to reality. Figure 9 shows the conventional constant gap and the varying gap. The latter is calculated from the

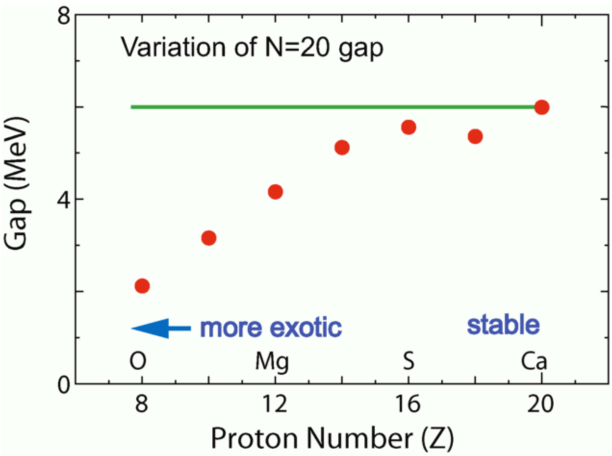


Fig. 9. (color online) Variation of N=20 gap as a function of Z. The dots are calculated from the shell model interaction sdpf-M containing appropriate amount of the tensor force. The horizontal bar is a conventional expectation of a constant gap.

sdpf-M interaction [35,36] which has been very successful for the shell model description of exotic Ne, Na, Mg, Al, Si isotopes, as discussed in *e.g.* [37–41]. A small gap for $Z$ smaller in Fig. 9 produces deformation for nuclei outside the Island of Inversion of [32], by bringing intruder dominant configurations into ground and low-lying states. Thus, the Island of Inversion is not like the one proposed by Warburton *et al* [32], and the "western" boundary of the Island should be moved and may not be sharp. Other boundaries may change from the original ones too.

## 4. Intriguing relevant topics

The proper inclusion of the tensor force is important also for the weak processes. Figure 10 indicates the ratios between two types of calculations; one (SFO) is with appropriate tensor force, while the other is with inappropriate amount of the tensor force. By including the tensor force, the cross section increases [42].

The last example is the magic numbers of superheavy nuclei. Figure 11 presents single particle energies of protons. Fig. 11(a) is obtained by a standard Woods-Saxon potential with $A$=300. In Fig. 11(b), the tensor force is added by using the $\pi + \rho$ meson exchange potential, and moreover the neutron $1k_{17/2}$ and $2h_{11/2}$ orbits are fully occupied. One sees how much single-particle energies vary due to the tensor force and particular configurations. The $Z$=114 magic number is washed away, whereas the $Z$=92 shows up. Details of the present calculation depend on the Woods-Saxon potential parameters. What we would like to emphasize is not the individual single particle energies but the size of the effect as well as the basic character of the change.

## 5. Summary

In summary, we have made manifest that the tensor force changes magic numbers and shell structure of exotic nuclei from those of stable nuclei. Its effect can be seen at

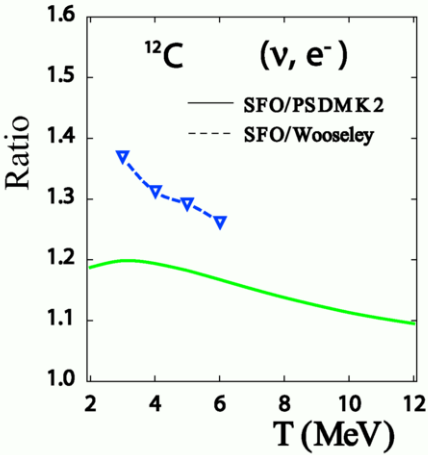


Fig. 10. (color online) Ratio of neutrino reaction cross section. SFO contains appropriate amount of tensor-force effects over the others. See [42] for details.

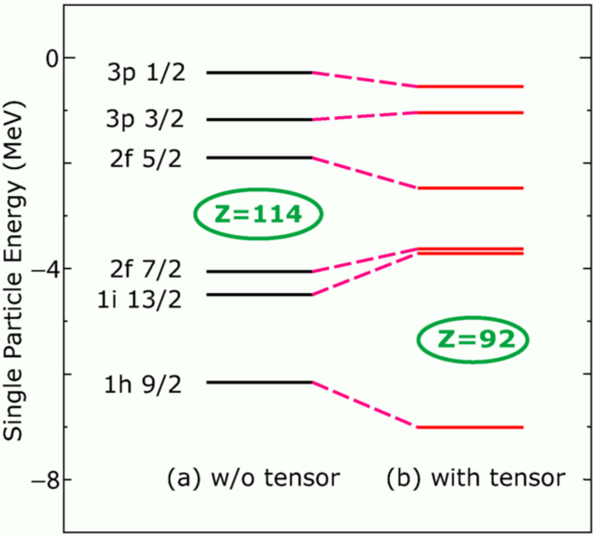


Fig. 11. (color online) Single-particle levels of protons around $Z$=114 with and without the tensor force.

many places on the nuclear chart. The tensor force can be crucial for deformation, and can affect the weak process transition strength. The variation of shell structure can be seen experimentally by considerably increasing the neutron number. Thus, we need RI-beam experiments to establish the properties of the tensor force. As the tensor force is characteristic to meson exchange processes, we can now see that Yukawa's forces create intriguing and exciting structures in exotic nuclei, and affect the nucleosynthesis through R-process *etc.* The structure of exotic nuclei may be more directly linked to the nucleon-nucleon interaction, because the stability and restoring force of the mean field become weaker. We mention that the tensor force has, in some cases, effects beyond single-particle energies even for low-energy spectrum [43].

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